



Measurement of Microwave Dielectric Properties of Particulate Materials

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(Received 25 February 1992; revised version received 10 November 1992;
accepted 8 December 1992)

ABSTRACT

Methods of measuring the dielectric properties of granular and powdered or pulverized materials at microwave frequencies are discussed. Factors affecting the dielectric properties of materials, such as frequency, moisture content, temperature and bulk density, are reviewed, and the nature of their influence is discussed. Dielectric properties measured for some particulate materials are presented to illustrate their variation with these variables. Relationships between the dielectric constants and loss factors of particulate materials and the bulk density of these materials are discussed, and data illustrating these relationships are presented. Dielectric mixture equations are identified for use in correlating the dielectric properties of particulate materials with their bulk densities and for use in estimating the dielectric properties of the particles from measurements of the dielectric properties and densities of particulate materials.

INTRODUCTION

Microwave dielectric properties of materials are important because they influence the way in which electromagnetic fields associated with microwave energy interact with the materials. Use of microwave energy for microwave dielectric heating of materials is an important application requiring information about the dielectric properties of the materials. Use of lower levels of microwave energy for measurements such as moisture content sensing is another important area for which dielectric properties information about the materials is essential. Often the materials for both types of applications may be particulate in nature, i.e. granu-

lar or powdered materials. This paper deals with measurements and relationships between variables associated with such particulate materials.

Definitions

The fundamental AC characteristics of materials have been defined in detail previously in terms of electromagnetic field concepts (Nelson, 1973a) and in terms of parallel-equivalent circuit concepts (Nelson, 1965). For practical use, the dielectric properties of usual interest are the dielectric constant ϵ' and the dielectric loss factor ϵ'' , the real and imaginary parts, respectively, of the relative complex permittivity, $\epsilon = \epsilon' - j\epsilon'' = |\epsilon|e^{-j\delta}$, where δ is the loss angle of the dielectric. Hereafter, 'permittivity' is understood to represent the relative complex permittivity; i.e. the permittivity relative to free space, or the absolute permittivity divided by the permittivity of free space, $\epsilon_0 = 8.854 \times 10^{-12}$ F/m. Often, the loss tangent, $\tan \delta = \epsilon''/\epsilon'$, or dissipation factor, is also used as a descriptive dielectric parameter, and sometimes the power factor ($\tan \delta / \sqrt{1 + \tan^2 \delta}$) is used. The conductivity of the dielectric in S/M is $\sigma = \omega\epsilon_0\epsilon''$, where $\omega = 2\pi f$ is the angular frequency, with frequency f in Hz. In this article, ϵ'' is interpreted to include the energy losses in the dielectric due to all operating dielectric relaxation mechanisms and ionic conduction. The loss factor is associated with energy dissipation or absorption from the alternating electric field in the material, whereas the dielectric constant is associated with the capability of the material for storing energy in the electric field in the material.

MEASUREMENT OF DIELECTRIC PROPERTIES

Techniques for the measurement of dielectric properties of materials are many and varied. At microwave frequencies, generally about 1 GHz and higher, transmission-line, resonant cavity, and free-space techniques have been useful. Principles and techniques of microwave dielectric properties measurements have been discussed in reviews of such methods (Westphal, 1954; Altschuler, 1963; Redheffer, 1964; Bussey, 1967; Franceschetti, 1967). With the development of suitable equipment for time-domain measurements, techniques were developed for measurement of dielectric properties of materials over wide ranges of frequency (Fellner-Feldegg, 1969; Nicolson & Ross, 1970; van Gemert, 1973; Kent, 1975; Kwok *et al.*, 1979; Bellamy *et al.*, 1985). Since modern microwave network analyzers have become available, the

methods of obtaining dielectric properties over wide frequency ranges have become even more efficient. Recent reviews have included methods for both frequency-domain and time-domain techniques (Kaatze & Giese, 1980; Afsar *et al.*, 1986).

Dielectric sample holder design for the specific materials is an important aspect of the measurement technique. The Roberts and von Hippel (1946) short-circuited line technique for dielectric properties measurements provides a suitable method for many materials. For this method, the sample holder can be simply a short section of coaxial-line or rectangular-waveguide with a shorting plate or other short-circuit termination at the end of the line against which the sample rests. This is convenient for particulate samples, because the sample holder, and also the slotted line or slotted section to which the sample holder is connected, can be mounted in a vertical orientation so that the top surface of the sample can be maintained perpendicular to the axis of wave propagation as required for the measurement. The vertical orientation of the sample holder is also convenient for particulate materials when the measurements are taken with a network analyzer instead of a slotted line.

Dielectric properties of cereal grains, seed and powdered or pulverized materials have been taken with various microwave measurement systems assembled for such measurements. Twenty-one-mm, 50- Ω coaxial-line systems were used for these measurements at frequencies from 1 to 5.5 GHz (Nelson, 1973*b*; Nelson *et al.*, 1980, 1989). A 54-mm, 50- Ω coaxial sample holder, designed for minimal reflections from the transition, was used with this same system for measurements on larger-kernel cereals such as corn (Nelson, 1979). A rectangular-waveguide X-band system was used to determine dielectric properties of grain and seed samples at 9 to 12 GHz (Nelson, 1972). A rectangular waveguide K-band system (Nelson, 1983*a*) was used for measurements on ground and pulverized materials for measurements at 22 GHz (Nelson *et al.*, 1980; 1989, You & Nelson, 1988; Nelson & You, 1989, 1990).

The Roberts and von Hippel method (1946) requires measurements to determine the standing-wave ratio (SWR) in the line with and without the sample inserted. From the shift in the position of the standing-wave node and changes in node widths related to SWRs, sample length and waveguide dimensions, etc., ϵ' and ϵ'' can be calculated with suitable computer programs (Nelson *et al.*, 1972, 1974). Similar determinations can be made with a network analyzer or other instrumentation by measurement of the complex reflection coefficient of the empty and filled sample holder.

Computer control of impedance analyzers (Lawrence *et al.*, 1989) and network analyzers (Waters & Brodwin, 1988) has facilitated the automatic measurement of dielectric properties over wide frequency ranges. Special calibration methods have also been worked out to eliminate errors caused by unknown reflections in the coaxial-line systems (Kraszewski *et al.*, 1983; Lawrence *et al.*, 1989).

Recently, microwave dielectric properties of wheat were determined at 4.8 and 9.4 GHz by free-space measurements with a network analyzer and the sample in a cubical dielectric container between horn antennas (Kraszewski & Nelson, 1990). Measurement of the complex transmission coefficient, the components of which are attenuation and phase shift, permits the calculation of ϵ' and ϵ'' .

The choices of measurement technique, equipment and sample holder design depend upon the dielectric materials to be measured, the frequency or frequency range of interest, the extent of the research, the equipment available and the resources available for the studies. Vector network analyzers are expensive, but very versatile and useful if studies are extensive. Scalar network analyzers and impedance analyzers are less expensive, but still too expensive for many programs. For limited studies, more commonly available microwave laboratory measurement equipment can suffice if suitable sample holders are constructed. When data are required at only one microwave frequency, a resonant cavity technique may be the logical choice (Bussey, 1967). Such cavities can be easily constructed with rectangular waveguide sections or from waveguide flanges and waveguide stock (Kraszewski *et al.*, 1990). Construction of a cylindrical cavity (Risman & Bengston, 1971) may be advantageous depending on the needs. For temperature-dependent studies, a cavity with provision for alternate dielectric properties measurement and microwave heating of the sample for temperature control may be advantageous (Bosisio *et al.*, 1986). At commonly used microwave frequencies, a measurement system can often be assembled from components available in microwave teaching laboratories, using a short waveguide section with a shortening plate as the sample holder (Nelson, 1972) and an available general computer program (Nelson *et al.*, 1972, 1974) for calculation of the dielectric properties.

VARIATION OF THE DIELECTRIC PROPERTIES

The dielectric properties of most materials vary with several different factors. In hygroscopic materials, the amount of water in the materials is generally a dominant factor. The dielectric properties also depend on the

frequency of the applied electric field, the temperature of the materials, and on the density and structure of the materials. In granular or particulate materials, the bulk density of the air-particle mixture is another factor that influences their dielectric properties. Of course, the dielectric properties of materials is dependent on their chemical composition and especially on the permanent dipole moments associated with water and any other molecules making up the materials of interest.

Frequency dependence

With the exception of some extremely low-loss materials, i.e. materials that absorb essentially no energy from microwave fields, the dielectric properties of most materials vary considerably with the frequency of the applied electric fields. This frequency dependence has been discussed previously (Nelson, 1973a). An important phenomenon contributing to the frequency dependence of the dielectric properties is the polarization arising from the orientation with the imposed electric field of molecules which have permanent dipole moments. The mathematical formulation developed by Debye (1929) to describe this process for pure polar materials can be expressed as

$$\epsilon = \epsilon_{\infty} + \frac{\epsilon_s - \epsilon_{\infty}}{1 + j\omega\tau} \quad (1)$$

where ϵ_{∞} represents the dielectric constant at frequencies so high that molecular orientation does not have time to contribute to the polarization, ϵ_s represents the static dielectric constant, i.e. the value at zero frequency (DC value) and τ is the relaxation time, the period associated with the time for the dipoles to revert to random orientation when the electric field is removed. Separation of eqn (1) into its real and imaginary parts yields:

$$\epsilon' = \epsilon_{\infty} + \frac{\epsilon_s - \epsilon_{\infty}}{1 + \omega^2\tau^2} \quad (2)$$

$$\epsilon'' = \frac{(\epsilon_s - \epsilon_{\infty})\omega\tau}{1 + \omega^2\tau^2} \quad (3)$$

The relationships defined by these equations are illustrated in Fig. 1.

Thus, at frequencies very low and very high with respect to the molecular relaxation process, the dielectric constant has constant values,

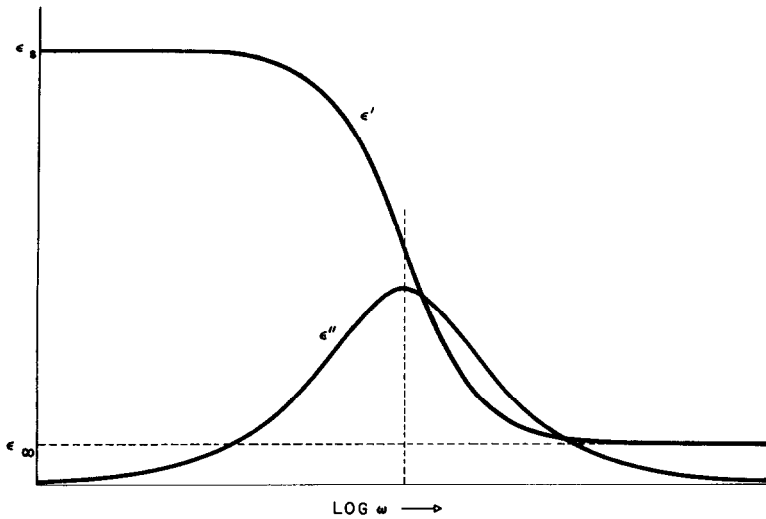


Fig. 1. Dispersion and absorption curves representing the Debye model for a polar substance with a single relaxation time.

ϵ_s and ϵ_∞ , respectively, and the losses are zero. At intermediate frequencies, the dielectric constant undergoes a dispersion, and dielectric losses occur with the peak loss at the relaxation frequency, $\omega = 1/\tau$.

The Debye equation can be represented graphically in the complex ϵ' versus ϵ'' plane as a semicircle with a locus of points ranging from ($\epsilon' = \epsilon_s$, $\epsilon'' = 0$) at the low-frequency limit to ($\epsilon' = \epsilon_\infty$, $\epsilon'' = 0$) at the high-frequency limit (Fig. 2). Such a representation is known as a 'Cole-Cole' diagram (Cole & Cole, 1941).

Since few materials of practical interest consist of pure polar materials with a single relaxation time, many other equations have been developed to describe better the frequency-dependent behavior of materials with more relaxation times or a distribution of relaxation times (Daniel, 1967; Hasted, 1973; Nelson, 1973a; Böttcher & Bordewijk, 1978). One such equation is the Cole-Cole equation (Cole & Cole, 1941).

$$\epsilon = \frac{\epsilon_s - \epsilon_\infty}{1 + (j\omega\tau)^{1-\alpha}} \quad (4)$$

where α denotes the spread of relaxation times, and this empirical relaxation-time distribution parameter takes on values between 0 and 1.

Water in its liquid state is a good example of a polar dielectric. The microwave dielectric properties of liquid water are listed in Table 1 for

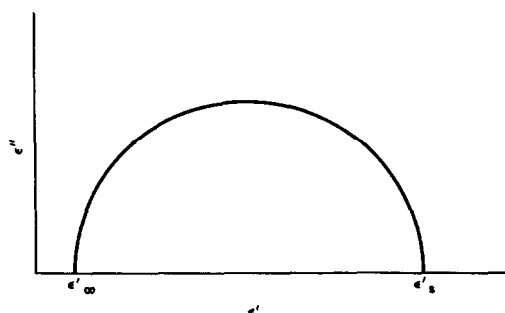


Fig. 2. Cole-Cole plot for a polar substance with a single relaxation time.

TABLE 1
Microwave Dielectric Properties of Liquid Water at Indicated Temperatures^a

Frequency (GHz)	20°C		50°C	
	ϵ'	ϵ''	ϵ'	ϵ''
0.577	80.3	2.75	69.9	1.25
1.744	79.2	7.9	69.7	3.6
3.00	77.4	13.0	68.4	5.8
4.63	74.0	18.8	68.5	9.4
9.14	63.0	31.5	65.5	16.5
9.37	62.0	32.0	64.5	17.0
12.47	—	—	61.5	21.4
23.62	30.9	35.7	48.3	30.6
24.19	29.6	35.2	48.7	31.1
26.78	—	—	44.2	32.0
34.88	19.2	30.3	35.4	33.1
36.3	—	—	34.3	32.6
890	4.3	2.28	4.3	3.51

^aHasted (1973).

several frequencies at 20 and 50°C. Each set of data can be presented in the form of a Cole-Cole diagram. The relaxation frequency, $(2\pi\tau)^{-1}$, and the static values of the dielectric constant ϵ_s for water at various temperatures are listed in Table 2. Since $\epsilon_\infty = 4.3$ can be considered temperature independent, and the relaxation-time distribution parameter α is also comparatively temperature independent with a relatively small value of 0.012, eqns (2) and (3), together with the relaxation parameters listed in Table 2, can be used to provide close estimates for the dielectric properties of water over a wide range of frequencies and temperatures.

TABLE 2
Dielectric Relaxation Parameters for Water^a

<i>Temperature (°C)</i>	<i>Relaxation frequency (GHz)</i>	ϵ_s
0	8.89	87.9
10	12.63	84.0
20	17.11	80.2
30	22.10	76.6
40	27.44	73.2
50	33.16	69.9
60	40.81	66.8
75	49.74	62.3

^aHasted (1973).

However, pure water rarely appears in its free liquid state in food products. Most often it is physically absorbed in material capillaries or cavities or chemically bound to other molecules of the material. Dielectric relaxations of absorbed water take place at lower frequencies than the relaxation of free water (Hasted, 1973). Depending upon the material structure, there may be various forms of bound water differing in energy of binding and in dielectric properties. In heterogeneous systems, Maxwell-Wagner relaxations are also possible (Hasted, 1973). Moist material, in practice, is usually an inhomogeneous mixture, often containing more than one substance with unknown dielectric properties. Thus, it is difficult to understand and predict the dielectric behavior of such material at different frequencies, temperature or hydration levels. At present, very little is known about the dielectric properties of moist materials of different structures containing various forms of bound water. However, a complete understanding is not always necessary for the solution of practical problems.

Temperature dependence

The dielectric properties of materials are also temperature dependent, and the nature of that dependence is a function of the dielectric relaxation processes operating under the particular conditions existing and the frequency being used. As temperature increases, the relaxation time decreases, and the loss-factor peak illustrated in Fig. 1 will shift to higher frequencies. Thus, in a region of dispersion, the dielectric constant will

increase with increasing temperature, whereas the loss factor may either increase or decrease, depending on whether the operating frequency is higher or lower than the relaxation frequency. The temperature dependence of ϵ_{∞} is generally negligible (Böttcher & Bordewijk, 1978), and while that of ϵ_s is larger, its influence is minor in a region of dispersion. Below the region of dispersion, the dielectric constant decreases with increasing temperature. Distribution functions can be useful in expressing the temperature dependence of dielectric properties (Böttcher & Bordewijk, 1978), but the frequency and temperature dependent behavior of the dielectric properties of most materials is complicated and can perhaps best be determined by measurement at the frequencies and under the other conditions of interest.

Density dependence

Since the influence of a dielectric depends on the amount of mass interacting with the electromagnetic fields, the mass per unit volume or density, will have an effect on the dielectric properties. This is especially notable with particulate dielectrics such as pulverized or granular materials. In understanding the nature of the density dependence on the dielectric properties of particulate materials, relationships between the dielectric properties of the solid materials and those of air-particle mixtures, such as granular or pulverized samples of such solids, are useful.

In some instances, the dielectric properties of a solid may be needed when particulate samples are the only available form of the material. This was true for cereal grains, where kernels were too small for the dielectric sample holders used for measurements (You & Nelson, 1988; Nelson & You, 1989) and in the case of pure minerals that had to be pulverized for purification (Nelson *et al.*, 1989). For some materials, machining of samples to exact dimensions required for dielectric properties measurement is difficult, and measurements on pulverized materials are more easily performed. In these examples, proven relationships for converting dielectric properties of particulate samples to those for the solid material are important. Therefore, some useful relationships that have been tested for this conversion of dielectric properties data are presented here. They include dielectric mixture equations and extrapolation of functions of the dielectric properties that are essentially linear with bulk density.

Two well-known dielectric mixture equations were found to perform satisfactorily for relatively low permittivity materials (Nelson & You, 1990). The notation used here applies to two-component mixtures,

where ϵ represents the permittivity of the mixture, ϵ_1 is the permittivity of the medium in which particles of permittivity ϵ_2 are dispersed, and v_1 and v_2 are the volume fractions of the respective components, where $v_1 + v_2 = 1$.

One of the mixture equations is the Complex Refractive Index equation:

$$(\epsilon)^{1/2} = v_1(\epsilon_1)^{1/2} + v_2(\epsilon_2)^{1/2} \quad (5)$$

and the other is the Landau and Lifshitz, Looyenga equation:

$$(\epsilon)^{1/3} = v_1(\epsilon_1)^{1/3} + v_2(\epsilon_2)^{1/3} \quad (6)$$

Functions of the real and imaginary parts of the relative complex permittivity of particulate materials, such as pulverized coal, wheat and whole-wheat flour, that are essentially linear with bulk density were identified previously (Nelson, 1983*b*). Linearity of $(\epsilon')^{1/2}$ and $(\epsilon'' + e)^{1/2}$, where e is a small constant, with bulk density is consistent with eqn (5). Linearity of $(\epsilon')^{1/3}$ with density is consistent with eqn (6). These linear relationships between functions of the dielectric properties and the bulk densities of particulate materials can be very useful.

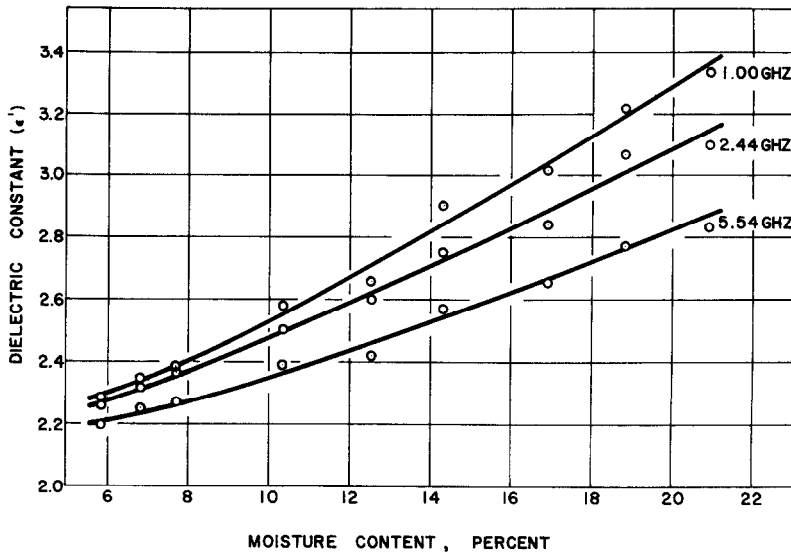
PARTICULATE MATERIAL DIELECTRIC PROPERTIES DATA

Some data obtained by measurements of the dielectric properties of particulate materials are presented here to illustrate the nature of their variation with the variables already discussed.

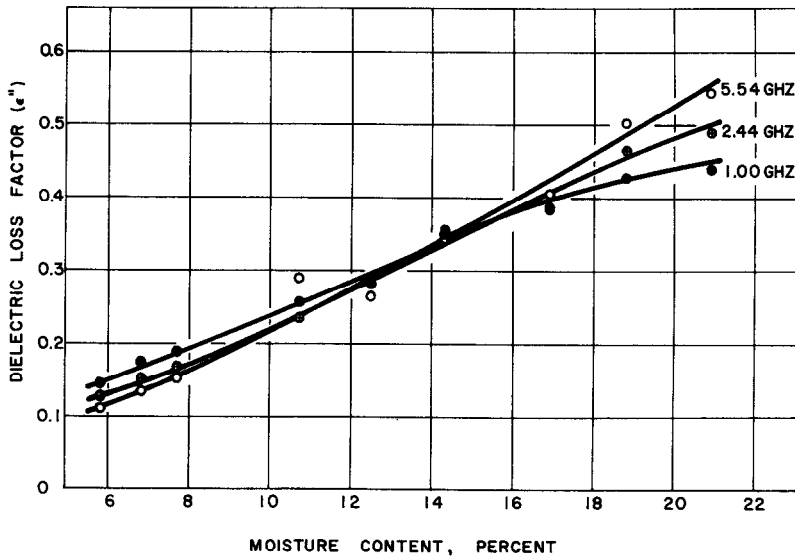
The variation of the dielectric constant and loss factor of hard red winter wheat with moisture content and frequency are illustrated in Fig. 3. Moisture contents are reported on a wet basis throughout this article. The decrease in the dielectric constant with increasing frequency indicates that these frequencies lie in a region of dispersion, but the loss factor data show very little dependence on frequency in the range from 1 to 5.5 GHz, particularly in the 10 to 16% moisture content range which is of practical interest.

The variation in the dielectric constant of shelled corn with temperature is illustrated in Fig. 4 at 2.45 GHz, as well as the lower frequencies of 20 and 300 MHz, at moisture contents of about 10 and 19%. Temperature dependent data of this kind have also been reported for a hard red spring wheat at 2.45 and 9.4 GHz (Chugh *et al.*, 1973).

The variation of the dielectric constant with natural bulk densities of shelled, yellow-dent field corn, achieved by loosely filling and settling



(a)



(b)

Fig. 3. Dependence of (a) the dielectric constant and (b) the dielectric loss factor of hard red winter wheat, *Triticum aestivum* L., on moisture content at indicated frequencies and 24°C (Nelson, 1973b).

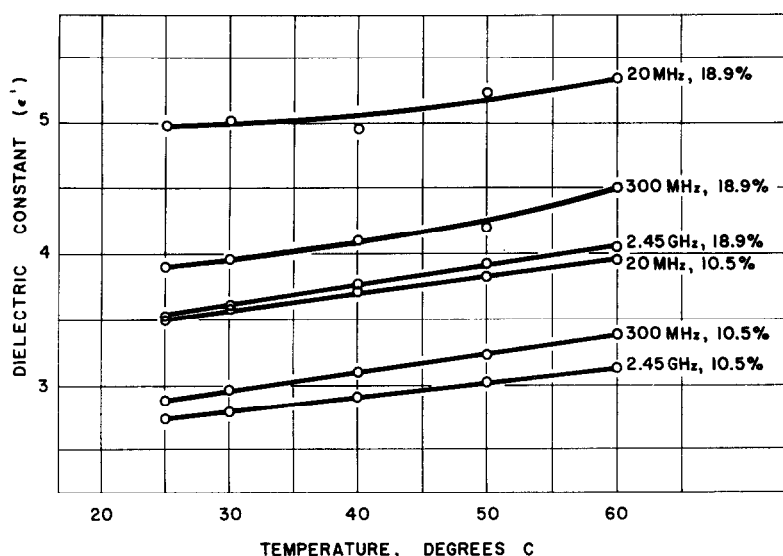


Fig. 4. Temperature dependence of the dielectric constant of shelled, yellow-dent field corn, *Zea mays* L., at indicated frequencies and moisture contents (Nelson, 1979).

samples in a coaxial cylindrical sample holder, is shown in Fig. 5 for several moisture contents at 2.45 GHz. Over narrow density ranges, the relationship appears linear, but nonlinear behavior has been noted for very wide density ranges achieved by crushing wheat kernels in the sample holder with a press, as shown in Fig. 6.

The nearly linear relationships between the dielectric constants of shelled corn and temperature and density was noted in Figs 4 and 5 and permitted the development of models for ϵ' as a function of moisture content, temperature and density at 2.45 GHz (Nelson, 1979). Further work resulted in models for ϵ' of several cereal grains and soybeans as functions of frequency, moisture content, temperature and density over wide ranges of all four variables (Nelson, 1987). A composite model for ϵ' and ϵ'' of cereal grains in general was also developed (Kraszewski & Nelson, 1989).

Equations (5) and (6) and the linear extrapolations of functions of the dielectric properties already mentioned that are consistent with these equations have been applied to measurements of the dielectric properties of granular and powdered materials for purposes of estimating the dielectric properties of the solid materials (Nelson, 1983*b*, 1984; Nelson *et al.*, 1989; Nelson & You, 1989, 1990; You & Nelson, 1988). For

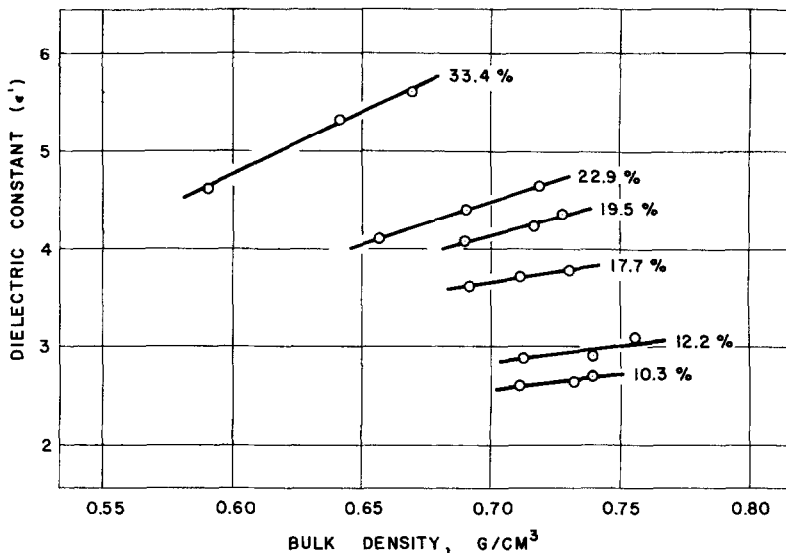


Fig. 5. Dependence of the dielectric constant of shelled, yellow-dent field corn, *Zea mays* L., of indicated moisture contents on bulk density at 2.45 GHz and 24°C (Nelson, 1979).

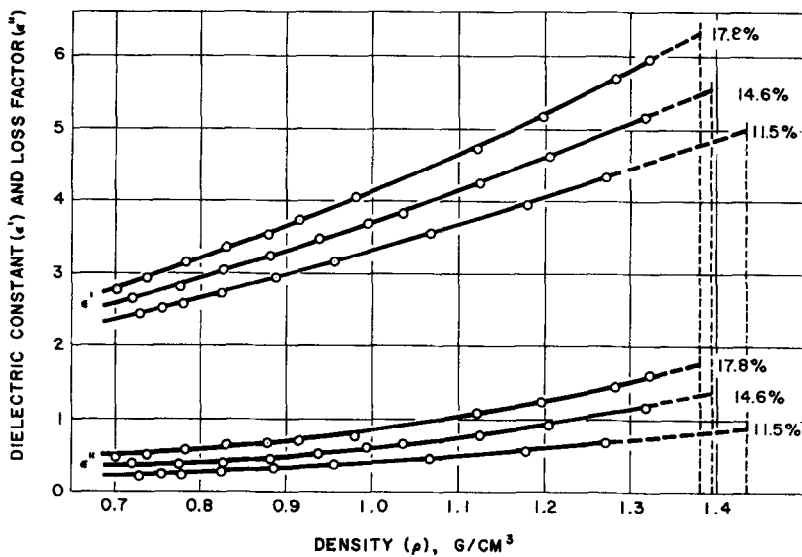


Fig. 6. Density dependence of the dielectric constant and loss factor of hard red winter wheat of indicated moisture contents at 9.4 GHz and 24°C (Nelson, 1976).

TABLE 3
Dielectric Properties (Permittivities) of Cereal Grain Kernels Estimated by Extrapolation of Linear Density Functions of the Dielectric Constant and Loss Factor and by Calculation from Indicated Dielectric Mixture Equations from Permittivity Measurements on Bulk Samples of Whole Kernel and Ground Grain Samples at 24°C^a

Material	Frequency (GHz)	Measured properties			Volume fraction	Estimated complex permittivity of kernels						
		Density g/cm ³		Permittivity, particulate material		Extrapolation of linear functions ^b			Dielectric mixture equations			
		Solid material	Particulate material			ϵ'	ϵ''	$(\epsilon')^{1/2}$	$(\epsilon')^{1/3}$	$(\epsilon'' + e)^{1/2}$	Refractive index	Landau & Lifshitz, Looyenga
ρ_s	ρ	ϵ'	ϵ''	ϵ'	ϵ''	ϵ'	ϵ''	ϵ'	ϵ''			
Whole-kernel hard red winter wheat, 11.5% m.c., cv. 'Scout 66' (Nelson, 1983b)	9.4	1.437	0.730 0.778 0.887 0.955 1.067 1.178 1.271	2.45 2.59 2.95 3.18 3.54 3.97 4.34	0.22 0.25 0.33 0.37 0.46 0.57 0.69	0.51 0.54 0.62 0.66 0.74 0.82 0.88	4.81 ± 0.27 4.98 ± 0.13 0.85 ± 0.04	4.46 4.52 4.67 4.73 4.78 4.88 4.95	0.59 0.61 0.68 0.69 0.71 0.77 0.83	4.77 4.82 4.93 4.96 5.01 5.03	0.68 0.69 0.76 0.76 0.77 0.82 0.86	

Ground hard red winter wheat, 10.9% m.c., cv. 'Scoutland' (Nelson, 1983b)	11.7	1.406	0.592	2.07	0.14	0.42	4.49 ± 0.14	4.64 ± 0.09	0.71 ± 0.06	4.17	0.49	4.51	0.57
			0.743	2.44	0.22	0.53				4.25	0.54	4.53	0.62
			0.797	2.61	0.24	0.57				4.35	0.55	4.61	0.63
			0.883	2.88	0.30	0.63				4.44	0.59	4.67	0.66
			0.994	3.18	0.40	0.71				4.44	0.67	4.62	0.71
			1.105	3.53	0.43	0.79				4.49	0.62	4.61	0.66
			1.148	3.70	0.47	0.82				4.54	0.63	4.65	0.67
Ground white rice, 12.2% m.c., cv. 'Lebonnet' (You & Nelson, 1988)	11.0	1.476	0.696	2.38	0.26	0.47	4.78 ± 0.14	4.97 ± 0.12	0.94 ± 0.07	4.63	0.75	5.00	0.89
			0.748	2.53	0.30	0.51				4.67	0.79	5.02	0.92
			0.811	2.70	0.34	0.55				4.71	0.83	5.03	0.95
			0.905	2.97	0.44	0.61				4.75	0.90	5.02	1.01
			1.011	3.27	0.51	0.68				4.74	0.90	4.96	0.99
			1.135	3.62	0.59	0.77				4.72	0.88	4.87	0.94
			1.228	4.02	0.68	0.83				4.87	0.90	4.98	0.94

^aTabular data rounded to one, two or three decimal places. All calculations performed on unrounded data.

^bCalculated values with extrapolated 95% confidence intervals.

illustration, data on measurements of whole kernel wheat and of ground wheat and rice are presented in Table 3. The dielectric properties of the kernels were estimated by the linear extrapolation technique (Nelson, 1988, 1992) and were determined also by complex algebraic calculation from dielectric properties and density data on the particulate samples with eqns (5) and (6) as follows:

$$\text{Complex Refractive Index, eqn (5): } \varepsilon_2 = \left[\frac{\varepsilon^{1/2} + v_2 - 1}{v_2} \right]^2 \quad (7)$$

$$\text{Landau and Lifshitz, Looyenga, eqn (6): } \varepsilon_2 = \left[\frac{\varepsilon^{1/3} + v_2 - 1}{v_2} \right]^3 \quad (8)$$

Equations (7) and (8) follow directly from eqns (5) and (6), respectively, when the permittivity of air, $1 - j0$, is substituted for ε_1 . The volume fraction for the particles is obtained as $v_1 = \rho/\rho_2$, where ρ is the bulk density of the air-particle mixture, and ρ_2 is the density of the particles. Results of these linear extrapolations and the calculations from the mixture equations are summarized for comparison in Table 3.

The moisture content of the grain and the grain cultivar are listed, along with references describing the measurements. Included also are the frequency at which measurements were made, the density of the solid material, as determined by air-comparison pycnometer measurements, and the densities and corresponding permittivities of the air-particle mixtures over a series of densities. Next are listed the solid permittivity values obtained by extrapolation and the permittivities predicted by calculation from the indicated mixture equations.

Extrapolation of the linear functions of density, $(\varepsilon')^{1/2}$, $(\varepsilon')^{1/3}$, and $(\varepsilon'' + e)^{1/2}$, (Nelson, 1988, 1992) result in one value each as the estimate for ε' or ε'' of the kernel, whereas, separate estimates of kernel ε' and ε'' are obtained for each density of the particulate material when using the dielectric mixture equations, as shown in Table 3.

For all three materials, the cube-root extrapolation predicted a higher value for ε' of the kernels than the square-root relationship; however, when the statistical uncertainty of the extrapolation is taken into account, as indicated by the extrapolated 95% confidence intervals, the ranges of these two extrapolated values overlap. The range of ε' values given by the Refractive Index equations over the range of densities and volume fractions includes the value obtained by the square-root extrapolation, since they are consistent relationships. Likewise, the range of ε' values provided by the Landau and Lifshitz, Looyenga equation includes the

value obtained by the cube-root extrapolation, since they are also consistent relationships.

Values for ϵ' provided by the mixture equations depend upon the density or volume fraction at which the samples were measured, increasing with increasing volume fraction. Loss factor values predicted for the kernels by the Refractive Index equation are somewhat smaller than the values obtained by extrapolation. Values of ϵ'' from the Landau and Lifshitz, Looyenga equation include the extrapolated values within their range. Unfortunately, the true values for ϵ' and ϵ'' of wheat and rice kernels are unknown, so it is difficult to evaluate the performance of the different methods for estimating the dielectric properties of the kernels. These same mixture equations and linear extrapolation techniques were tested in similar measurements on two plastic materials which could be measured in both solid and pulverized forms for checking the performance of the estimation methods (Nelson & You, 1990). For these two plastic materials, one lossless and one with loss factors similar to grain, the Refractive Index and Landau and Lifshitz, Looyenga equations and their corresponding linear extrapolation techniques gave reliable results. The error in predicting ϵ' for the lossless material was within about 1%, and the Landau and Lifshitz, Looyenga equation, which was the closest of the two equations for the lossy plastic, was about 4% high. As losses increase with increasing moisture contents, larger errors can probably be expected in predicting solid material permittivities from measurements on higher moisture particulate materials with these techniques.

Dielectric mixture equations, eqns (5) and (6), provide a method for adjusting the dielectric properties of granular and powdered materials with characteristics similar to grain products from known values at one bulk density to corresponding values for a different bulk density. It follows from eqn (6), since $v_2 = \rho/\rho_2$, that the permittivity of an air-particle mixture of density ρ_x is given by

$$\epsilon_x = \left[[(\epsilon_y)^{1/3} - 1] \frac{\rho_x}{\rho_y} + 1 \right]^3 \quad (9)$$

where permittivity ϵ_y is known at density ρ_y .

Models already mentioned have been developed for estimating the dielectric properties of cereal grains and soybeans as functions of frequency, moisture content and density (Nelson, 1987; Kraszewski & Nelson, 1989). The dielectric properties of many agricultural products, including animal tissues, foods, plant materials, fruits and vegetables, grain and seed, wood, and textiles were included in extensive tabulations

prepared previously (Nelson, 1973*a*; Tinga & Nelson, 1973). More recently, an extensive tabulation and bibliography on dielectric properties of food materials has been published (Kent, 1987). These references provide data on many agricultural and food materials for certain frequencies and other specified conditions, but data are still not available for many materials, and they must be determined by measurement under specific conditions for reliable information on their dielectric properties.

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